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MULTI-AGENT TECHNOLOGY FOR AIRSPACE CONTROL IN THE COMBAT ZONE

Advanced Technical Concepts

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Successful airspace control is one of the key factors maximizing the effectiveness of air operations. It includes long and short-term planning and control that utilizes large and dynamic databases, and constitutes a combination of resource allocation, routing, scheduling, and deconfliction tasks performed repeatedly reflecting the battlefield dynamics. These tasks place heavy burden on personnel, leading to costly inefficiencies. Modern computing technologies are capable of expanding the share of airspace control functions performed by computers resulting in numerically justified decisions that will enhance planning and reduce pressure on its personnel without freeing them from the ultimate responsibility. The resultant problem is to be decomposed and its particular subsets are obtained in a decentralized, but coordinated fashion. This approach is best served by the "multi-agent" system technology that has been successfully deployed as the computational engine behind the airspace control system. The resultant software tool features the distributed coordination mechanisms based on collective decision-making and knowledge sharing, agent architecture and specific agents responsible for data collection/updating and planning/scheduling/deconfliction tasks, and the required visualization technology.

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1. ABSTRACT

Successful airspace control is one of the key factors maximizing the effectiveness of air operations. It includes long and short-term planning and control that utilizes large and dynamic databases, and constitutes a combination of resource allocation, routing, scheduling, and deconfliction tasks performed repeatedly reflecting the battlefield dynamics. These tasks place heavy burden on personnel, leading to costly inefficiencies. Modern computing technologies are capable of expanding the share of airspace control functions performed by computers resulting in numerically justified decisions that will enhance planning and reduce pressure on its personnel without freeing them from the ultimate responsibility. The resultant problem is to be decomposed and its particular subsets are obtained in a decentralized, but coordinated fashion. This approach is best served by the "multi-agent" system technology that has been successfully deployed as the computational engine behind the airspace control system. The resultant software tool features the distributed coordination mechanisms based on collective decision-making and knowledge sharing, agent architecture and specific agents responsible for data collection/updating and planning/scheduling/deconfliction tasks, and the required visualization technology. It has been validated by a comprehensive case study.

2. OVERVIEW

Successful airspace control is one of the key factors maximizing the effectiveness of air operations and the entire combat operation. It includes long and short-term planning and scheduling, and real-time control. These functions utilize a large and dynamic database and constitute a very complex combination of resource allocation, space allocation, routing, scheduling, deconfliction, and control tasks that are to be solved under information uncertainty and rigid time constraint. These tasks must be performed periodically to accommodate for the continuously arriving new information reflecting the dynamics of the battlefield operation. The Airspace Control Authority (ACA) has highly trained personnel utilizing their knowledge, experience, and intuition to perform all necessary ACA functions. However, the complexity of the tasks, large volumes of data to be analyzed and stringent time requirements, place a heavy burden on individual planners that combined with the entire scope of issues labeled as "human factor," may adversely affect the quality and timeliness of ACA decisions. Consequently, these could be among the factors limiting the success of the air campaign and preventing advanced military equipment and personnel to utilize their potential to the fullest. Availability of modern computing technologies creates the conditions when the share of ACA functions performed by computers could be expanded resulting in numerically justified decisions and reduced pressure on its personnel. This effort is aimed at the development of a computer-based system technology that will enhance ACA operation providing ever-increasing support to its personnel without freeing them from the ultimate responsibility.

An air traffic control system of the future is visualized as a fully decentralized, automated computer-based system. Such a system would allow for the utilization of the capabilities of personnel, equipment, and munitions to their full potential, as well as assuring the maximum safety of the air operation. A battlefield environment is highly dynamic. The decentralization results in the most flexible air operation control system that can easily accommodate for the rapidly changing situations providing that the necessary information is obtained and processed in a timely fashion. The latter could be achieved only by computer-based, fully automatic data acquisition and decision support. These considerations are implemented in the system for air traffic control in the battlefield zone presented herein with the goal of the maximum utilization of rapidly changing data and providing timely decision support to personnel of ACA (Wickens et al., 1998).

The solution to an air traffic control/planning problem is sought in the spatial, functional, and time domains. The *spatial aspect* of the problem deals with geographical maps, coordinates of the air bases, targets, airborne refueling stations and hazardous areas, and the utilization of airspace. It results in the definition of rational and safe routes for particular aircraft connecting the base of original deployment to the target or multiple targets, and to the designated landing base, when necessary through refueling areas. The f*unctional aspect* of the problem addresses the task assignment to particular pilots/aircraft, weapons-to-targets assignment, and the logistics of the entire air operation. The *time-domain aspect* of the problem includes the scheduling of the operation of particular aircraft at the take-off and landing stages, in-air refueling, and engaging targets. It could be seen that every aspect of the planning process is dictated by the tactical and intelligence information, affected by weather, and is consistent with the technical characteristics of aircraft, weapons, and targets. The system is expected to compile better-than-average air traffic control plans that will be presented for approval to ACA personnel in the enhanced, user-friendly format, which would complete the planning stage of the process.

The computer-based system represents the "big picture" of the airspace control problem in the *spatial-domain*, *functional-domain* and *time-domain* based on a mathematical model. Particular entities of the model "live" in the simulation environment and as such, obey laws of mechanics and aerodynamics, engage in communication among themselves and with the mission control, expend fuel and ammunition, experience various hazards, sustain battlefield damage, etc., and ultimately provide invaluable feedback for the enforcement of particular considerations and rules of engagement, detection of conflicts and deconfliction, and assessment of the "goodness" of the planning decisions. The system obtains numerical solutions of the particular subsets of the airspace control problem and coordinates "local," independently obtained solutions, thus resulting in conflict-free, long and short-term plans and schedules. The intermediate solutions are coordinated and deconflicted with the enforcement of specific considerations. The entire solution task is visualized as an ongoing, iterative process driven by continuously updated databases reflecting the battlefield dynamics and newly arrived data. The capability of incorporation of human expertise presented in a formalized and intuitive fashion, and accommodation of new rules, considerations, and conditions is viewed as an important feature of the system.

Operation of the system includes planning and execution stages. At the planning stage, the plan of the entire air operation utilizing time-invariant data, such as geographical and performance characteristics of the aircraft, and a priory given information, such as the initial description of the air operation, is established. The execution stage addresses the effect of all factors preventing the implementation of the accepted plan of air operation, as well as the possible deviations from the plan. In order to assure the completion and overall success of the operation, the proposed system has the capability of rapid re-planning (deconfliction) achieved at the lowest possible cost. This process must employ some collaboration/negotiation between the involved entities. It facilitates the control of the air operation and is accomplished by providing updated assignments to individual pilots in a timely fashion. Consequently, the proposed system should perform the data acquisition task on a continuous basis and utilize reliable and secure communication channels with individual aircraft, as well as successful visualization techniques.

In many ways, the realization of the above capabilities is well served by the implementation of multi-agent system technology that has been successfully deployed for a number of large-scale software engineering projects for industrial and military applications (Wooldridge and Jennings, 1995) and specifically for airspace control (Tomlin et al., 1997), (Hill et al., 2005). Recent advancements in multi-agent system technology provide the means for the development of fully automated planning, scheduling, and operation control systems for complex, multivariable processes exhibiting hybrid (both continuous and discrete) behavior. Modern multi-agent systems emulate complex collaboration and information exchange processes taking place within a group of human experts engaged in finding a compromise solution of complex problems. Driven by mathematically justified procedures and utilizing high-speed computers, these systems consistently generate better-than-average and very prompt solutions that could be continuously updated on the basis of most recent information available. Unsurprisingly, multi-agent system technology has been chosen for the development of the ACA system

This project, jointly conducted by the Advanced Technical Concepts and the Gerstner Laboratory of the Czech Technical University of Prague, has resulted in a fully operational prototype of a multi-agent system AGENTFLY providing decision support to ASA. Its development became possible due to the successful solution of the following problems:

1. Mathematical modeling of the “big picture” in the *functional-domain*, *spatial-domain* and *time-domain*, utilizing various practical aspects of the air operation planning process such as types of manned and unmanned air vehicles and their unclassified characteristics, types of hazards, types of targets, existing practices and safety considerations, etc.

2. Numerical solution of the particular subsets of the airspace control problem and coordination of “local”, independently obtained solutions thus resulting in a conflict-free long-term and short-term plans and schedules.

3. Continuous data acquisition addressing the dynamics of the battlefield, status of the aircraft and weather thus facilitating the ongoing, iterative solution process driven by continuously updated databases.

4. Implementation of the physical realities of the problem in the individual software agents capable of negotiation leading to a numerical solution of the planning, deconfliction and execution tasks. Gerstner Laboratory of the Czech Technical University of Prague made various advancements in the multi-agent system technology adopting its major features for the solution of the above tasks resulting in the AGENTFLY tool.

5. Incorporation of the extensive experience in the practice of air space control in the battlefield zone, unclassified specifics of aircraft, implementation of planning and safety considerations by both pilots and air traffic controllers, interface with the existing software and databases, etc., provided by Advanced Technical Concepts, in the AGENTFLY. This led to the development of a system that is flexible, capable of on-going incorporation of human expertise presented in formalized and intuitive fashion, upgradeable by inclusion of new rules, considerations and conditions.

6. The resultant system offers advanced visualization, utilizes advanced graphics and graphic interfaces making it user-friendly. It has the potential for becoming an integral part of the ACA operation.

7. The developed technology is validated by a comprehensive illustrative case study, featuring a sophisticated scenario of an air operation. The case study, recorded on a CD, has been disseminated among relevant government organizations (AF, OSD, FAA) for possible adoption, further development and incorporation in the existing computer systems, and as a demonstrator of multi-agent system technology.

8. Successful completion and demonstration of the results of this project prompted its most recent development: a study of the relevance and applicability of the developed technology to the short-term and long-term plans of the FAA that include further development of computer support systems for air traffic controllers.

3. SPECIFICS OF THE AIRSPACE CONTROL PROBLEM

Solution of the airspace control problem results in an Airspace Control Plan (ACP) that allocates critical battlefield resources, equipment, space, and time reflecting

- Rules of engagement and disposition of air defense weapon systems,
- Air, land and maritime situations in the area of responsibility such as existing equipment limitations, electronic warfare, and C4 requirements that may adversely affect adherence to the ACP,
- Anticipated restricted area based on initial deployment of friendly forces and bases,
- Existing air traffic control areas, base defense zones, controlled or uncontrolled airspace, and overflight of neutral nations,
- Mission profiles, combat radii, and identification capability of aircraft operating in the area of responsibility,
- Enemy air defense weapons capabilities, deployment, and electronic attack/deception capabilities,
- Emergency procedures for aircraft experiencing difficulties,
- Procedures for day, night, and adverse weather conditions,
- Procedures for en route and terminal area air traffic control procedures for aircraft transitioning to and from the battle area that complement planned combat requirements,
- Procedures to support surge operations requiring high volumes of air traffic,
- Enemy offensive air capabilities, vulnerability of defensive counter aircraft to enemy surface-to-air missiles and vulnerability of friendly surface-based air defenses to enemy long-range artillery (Airspace…, 2005).

It is important that a straight-forward attempt to plan/schedule the missions unavoidably requires that the following issues be addressed:

1. *Traffic hazards* i.e. potential conflicts with other objects on the surface or in flight such as other aircraft, missile launches, or other potential hazards characterized by the number, type, position, and intent available via surveillance.
2. *Current en route weather hazards* including hail, icing, turbulence, high winds associated with thunderstorm activity, thunderstorm activity over oceanic airspace, wind shear

and microburst alerts, intensive precipitation, and areas of low visibility and tornadoes. This information is available from the Global Weather Information System.

3. *Rational airspace utilization* due to the fact that the value of the airspace for all users becomes increasingly critical as military operations, commercial operations, general aviation, rocket launches, and artillery shells compete for airspace. Airspace use/availability information is dynamic; it allows utilizing available airspace to enhance flight operations for both mission and economic priorities.

4. *Aircraft-to-airspace separation* ensures that aircraft maintain a safe distance from special use airspace, such as hazardous and warning areas defined via intelligence and surveillance data and regulatory publications and specific control instructions. Separation standards ensure that aircraft remain at an appropriate minimum distance from such areas.

5. *Aircraft-to-aircraft en route separation* in airspace ensures that a safe distance is maintained between aircraft. Separation standards are defined for the different aircraft operating environments. They separate aircraft using standard rules for vertical, lateral, and longitudinal separation. When potential conflicts exist, an air traffic planner evaluates the situation and develops conflict resolution alternatives. Special rules exist for aircraft to aircraft separation services in oceanic airspace.

6. *Aircraft-to-aircraft separation in terminal airspace* ensures that a safe distance is maintained between aircraft. Within terminal airspace, requirements for separation vary by airspace Class. There are standard rules for vertical, lateral, and longitudinal separation methods. When potential conflicts exist, an air traffic planner evaluates the situation and develops conflict resolution alternatives.

7. *Aircraft-to-terrain/obstacle separation* that ensures that aircraft maintains a safe distance from terrain and obstacles.

8. *Current Surface Separation* that prevents taxi conflicts and runway incursions.

Consequently, the planning process constitutes a number of parallel, semi-autonomous tasks, utilizing common, continuously updated databases that are aimed at the detection and resolution of the conflicts. The solution process is typically decentralized and results in “local” solutions reflecting “local” criteria and constraints that must be coordinated in the interests of the overall solution (FAA 2005).

4. EXISTING PRACTICES OF AIR TRAFFIC CONTROL

The air traffic control system is a vast network of people and equipment that ensures the safe operation of commercial and private aircraft. Air traffic controllers coordinate the movement of air traffic to make certain that planes stay a safe distance apart. Their immediate concern is safety, but controllers must also direct planes efficiently to minimize delays. Some regulate airport traffic through designated airspaces; others regulate arrivals and departures.

Although *airport tower controllers* or *terminal controllers* watch over all planes traveling through the airport's airspace, their main responsibility is to organize the flow of aircraft into and out of the airport. Relying on radar and visual observation, they closely monitor each plane to ensure a safe distance between all aircraft and to guide pilots between the hangar or ramp and the end of the airport's airspace. In addition, controllers keep pilots informed about changes in weather conditions such as wind shear, a sudden change in the velocity or direction of the wind that can cause the pilot to lose control of the aircraft.

During arrival or departure, several controllers direct each plane. As a plane approaches a base, the pilot radios ahead to inform the terminal of the plane's presence. The controller in the radar room, just beneath the control tower, has a copy of the plane's flight plan and already has observed the plane on radar. If the path is clear, the controller directs the pilot to a runway; otherwise, the plane is fitted into a traffic pattern with other aircraft waiting to land. As the plane nears the runway, the pilot is asked to contact the tower. There, another controller, who also is watching the plane on radar, monitors the aircraft the last mile or so to the runway, delaying any departures that would interfere with the plane's landing. Once the plane has landed, a ground controller in the tower directs it along the taxiways to its assigned gate. The ground controller usually works entirely by sight and/or relies on radar information if visibility is very poor.

The procedure is reversed for departures. The ground controller directs the plane to the proper runway. The local controller then informs the pilot about conditions at the airport, such as weather, speed and direction of wind, and visibility. The local controller also issues runway clearance for the pilot to take off. Once in the air, the plane is guided out of the airbase's airspace by the departure controller.

After each plane departs, airbase tower controllers notify *enroute controllers* who will now take charge. Nationally, there are 20 air route traffic control centers located around the country, each employing 300 to 700 controllers, with more than 150 on duty during peak hours at the busiest facilities. Airplanes usually fly along designated routes; each center is assigned a certain airspace containing many different routes. Enroute controllers work in teams of up to three members, depending on how heavy traffic is; each team is responsible for a section of the center's airspace. A team, as exemplified by commercial aviation, might be responsible for all planes that are between 30 and 100 miles north of an airport and flying at an altitude between 6,000 and 18,000 feet.

To prepare for planes about to enter the team's airspace, the radar associate controller organizes flight plans coming off a printer. If two planes are scheduled to enter the team's airspace at nearly the same time, location, and altitude, this controller may arrange with the preceding control unit for one plane to change its flight path. The previous unit may have been another team at the same or an adjacent center, or a departure controller at a neighboring terminal. As a plane approaches a team's airspace, the radar controller accepts responsibility for the plane from the previous controlling unit. The controller also delegates responsibility for the plane to the next controlling unit when the plane leaves the team's airspace.

The radar controller, who is the senior team member, observes the planes in the team's airspace on radar and communicates with the pilots when necessary. Radar controllers warn pilots about nearby planes, bad weather conditions, and other potential hazards. Two planes on a collision course will be directed around each other. If a pilot wants to change altitude in search of better flying conditions, the controller will check to determine that no other planes will be along the proposed path. As the flight progresses, the team responsible for the aircraft notifies the next team in charge of the airspace ahead. Through team coordination, the plane arrives safely at its destination.

Both tower and enroute controllers usually control several planes at a time; often, they have to make quick decisions about completely different activities. For example, a controller might direct a plane on its landing approach and at the same time provide pilots entering the airport's airspace with information about conditions at the airport. While instructing these pilots, the controller also might observe other planes in the vicinity, such as those in a holding pattern waiting for permission to land, to ensure that they remain well separated.

In addition to airbase towers and enroute centers, air traffic controllers also work in flight service stations operated at more than 100 locations nationally. These *flight service specialists* provide pilots with information on the station's particular area, including terrain, preflight and inflight weather information, suggested routes, and other information important to the safety of a flight. Flight service specialists help pilots in emergency situations and initiate and coordinate searches for missing or overdue aircraft. However, they are not involved in actively managing air traffic.
Some national air traffic controllers work at the FAA's Air Traffic Control Systems Command Center in Herndon, VA, where they oversee the entire system. They look for situations that will create bottlenecks or other problems in the system, and then respond with a management plan for traffic into and out of the troubled sector. The objective is to keep traffic levels in the trouble spots manageable for the controllers working at enroute centers.

The FAA has implemented an automated air traffic control system, called the National Airspace System (NAS) Architecture. The NAS Architecture is a long-term strategic plan that will allow controllers to more efficiently deal with the demands of increased air traffic. It encompasses the replacement of aging equipment and the introduction of new systems, technologies, and procedures to enhance safety and security and support future aviation growth. The NAS Architecture facilitates continuing discussion of modernization between the FAA and the aviation community (Nolan, 1990).

While the above description primarily reflects the operation of commercial aviation, it provides sufficient detail for the purpose of this project.

5. MULTI-AGENT PLANNING AND EXECUTION PROCESSES

In the nearest future, the advanced methods of computer science and artificial intelligence will play a pivotal role in air traffic control of military and civilian as well as manned and unmanned aerial vehicles. We have been investigating the use of agent based technology and the multi-agent algorithms for deployment in this specific application domain.

Multi-agent system is a collection of loosely coupled autonomous programs that perform collective behavior and collective decision making by means of interaction, negotiation, cooperation but also methods of teamwork, competition or social dominance. Multi-agent system domain provides a wide selection of ready to use COTS or open source integration platforms as well as various techniques and algorithms suitable for different coordination tasks.

The use of this highly innovative technology is appropriate in the situations where the data required for decision making are not available centrally. As air traffic control domain needs to move to less human driven problem and a problem more suited for automated decision making, we expect that substantial amount of computation and data maintenance will be onboard of the aircraft. Similarly, the future air-traffic operation (especially in battle-field or surveillance operations) will require techniques implementing safe, fast and robust deconfliction algorithms and would allow for other replanning scenarios in highly dynamic and unpredictable environment.

This expectation leads to investigation of a highly decentralized decision making systems that will make an important use of the available multi-agent technologies. Operation of a multi-agent air traffic control system is supposed encapsulate the following 3 decision making phases:

5.1. Data acquisition

Time-invariant data includes geographical information (digital map); performance characteristics of aircraft, primarily operational speed ranges and fuel burn rates given for various Standard Configuration Loads (STL); coordinates of the friendly airbases; and airspace design (aircraft separation) criteria that could be defined for various visibility conditions (i.e., sizes of the air corridors and tunnels, and communication, alert, safety, and collision zones around aircraft). Airspace design criteria are established based on the capability of aircraft to accurately fly and maintain pressure altitudes in higher altitude cruise and based on the capability of the aircraft and the relationship to separation criteria in lower altitude situations. Airspace design criteria for flight objects for a special use (hazardous/restricted) airspace activity include the time duration and volume of airspace around the trajectory required to execute the mission. This addresses dynamic airspace restrictions with variable separation for security, military operations, remotely operated aircraft, and reusable launch vehicles. *Time-varying data* includes the plan of the air operation that designates targets for particular aircraft (pilots) and assigns weapons to target and defines the NET (not earlier than) and NLT (not later than) times for particular target; weather-related information; coordinates and status of particular targets; and hazardous areas, also known as special use airspace (areas defended by SAMs, areas occupied by flying artillery shells, rocket launches, etc.). It could be seen that this information reflects the battlefield dynamics, i.e., changing goals of the air operation, neutralization of targets and detection of new targets and hazardous areas, changing weather conditions, etc. Finally, *reported data* represents the current status of the particular aircraft, such as payload, technical status, available fuel status, and actual aircraft position.

5.2. Initial planning

The first step of the initial planning process begins with establishing a logical time schedule for the neutralization of particular targets that constitute a subset of the air operation plan. This is followed by assigning aircraft/weapons to targets, selection of take-off airbases, and the bases where aircraft are to return after the completion of the mission. Temporal coordinates of the rest of the node points are to be calculated based on the average speed of the aircraft and the geometrical distance between the appropriate locations. At the next step of the initial planning, all intermediate points of the aircraft paths are to be calculated by interpolation, assuming that the node points are connected by straight lines in the four-dimensional space. The number of intermediate points is defined according to some chosen time step and average speed of the aircraft.

5.3. Deconfliction

The flight plans that are results form the initial planning process may contain possible conflicts and collision situations. Collision avoidance is not solved during the initial planning process due to high computational requirements related to this process and due to high dynamics of expected flight traffic. The detection and resolution of the conflicts criteria utilized in this process are defined based on the capability of aircraft to accurately fly and maintain required altitudes. Criteria for flight objects for a special use (hazardous/restricted) airspace activity include the time duration and volume of airspace around the trajectory required to execute the mission. This addresses dynamic airspace restrictions with variable separation for security, military operations, remotely operated aircraft, and reusable launch vehicles. It should be emphasized that detection and resolution of the conflicts takes into consideration weather conditions, time of the air operation, and the geographical region that dictates the size of the air corridors, air tunnels, communication, and alarm and danger zones surrounding aircraft.

The deconfliction process can be physically embedded in the initial planning phase or fight execution phase, described below. If deconfliction is to be executed during initial planning it needs to be implemented on top of a multi-agent simulation of the flight-plans elaborated during the initial planning process. Possible collisions will be resolved by the multi-agent deconflcition methods and log of the resulting operation will provide the final non-conflicting plans. More natural alternative is to implemented deconfliction within the flight execution process. The aircraft would follow their mission plan and carry out deconfliction process up in the air. This concept is referred to as *free-flight* and is particularly suitably for unmanned aerial vehicle operation.

5.4. Flight execution

The execution stage addresses the effect of all factors preventing the implementation of the accepted plan of air operation. These factors include unexpected changes in weather conditions, damage sustained by particular aircraft, actual fuel status, newly detected targets and hazardous zones, failure to neutralize targets according to the plan, failure to follow the required schedule, failure to stay within the designated corridor/tunnel, etc. It could be seen that in addition to making the goals of air operation unattainable, these factors can result in additional conflicts. In order to minimize the effect of these factors on the completion and overall success of the operation, the proposed system has the capability of rapid re-planning (deconfliction) achieved at the lowest possible cost. This process must employ some collaboration/negotiation between the involved entities. It facilitates the control of the air operation and is accomplished by providing updated assignments to individual pilots in a timely fashion. Unlike the initial planning, conflict resolution at this stage implies a decision process that takes into account when reported (real) data on technical status of the involved aircraft is available, amount of fuel on board, and the aircraft position.

6. IMPLEMENTATION ASPECTS

The agent-based air traffic based on the architecture listed in the previous section has been designed recently and has been implemented on top of the *A*-**globe** multi-agent platform (Sislak et al., 2005) and has been presented at (Pechoucek et. al, 2006). The system features technology for agent based flight modeling, air-traffic planning mechanism for a single plane, rule-based and utility based deconfliction mechanisms (See Fig. 1.). Specific negotiation-based conflict resolution procedures have been developed and implemented in multi-agent environment originally suggested by (Schulz et al. 1997), (Tomlin et al. 1997), and further developed for airspace deconfliction by (Pechoucek et al. 2006). The deconfliction mechanism is distributed by its nature that allows for addressing the high volume of computations associated with the solution of this problem.

Currently, massive scalability tests are under development. The developed system also provides 3-dimensional and web-accessible 2-dimensional presentation (GUI) layer (see Fig. 2). The system performs data-fusion on top of various data from freely available data-sources that have been integrated in the system (e.g. mosaic of Landsat7 images, USGS geographical data, GNIS name-related data, but also almost real-time data from the airport traffic monitors of major U.S. airports).

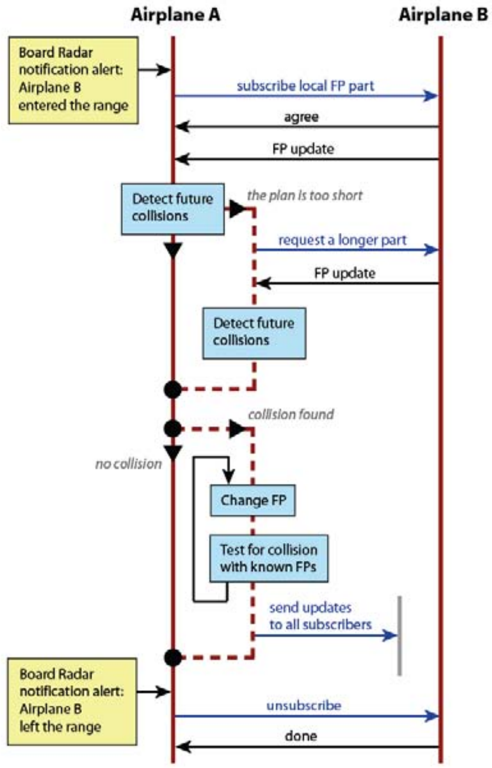

Figure 1. Deconfliction Negotiation Protocol

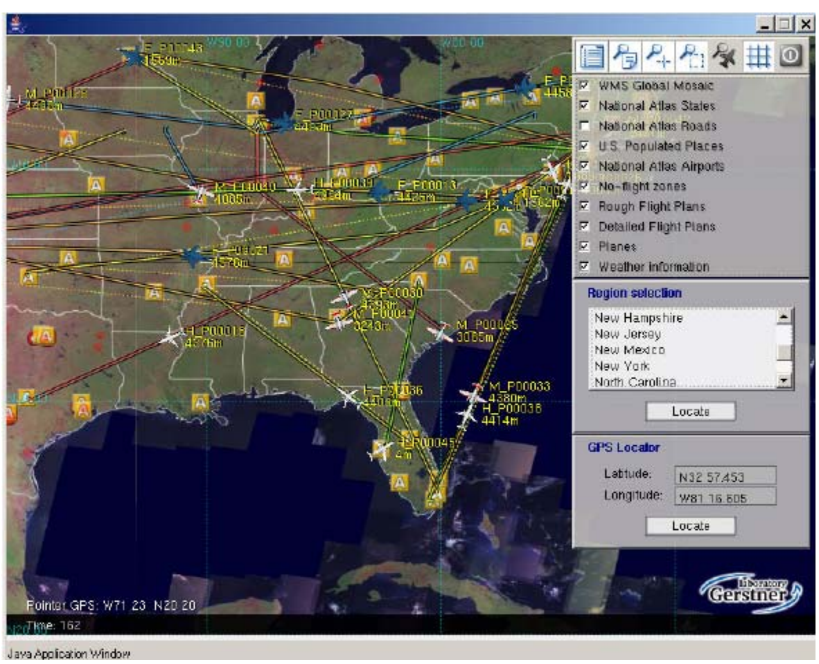

Figure 2. Presentation Layer

7. QUANTIFYING THE PROBLEM IN A MULTI-AGENT ENVIRONMENT

Air traffic planning results in a flight plan for each participating aircraft that assures that the goals of the air operation are fulfilled in the most safe and efficient fashion. The flight plan is represented by a sequence of waypoints established in the specially defined state space. Safety issues are to be addressed through the existing planning considerations incorporated in the computational procedure responsible for the definition of the waypoints.

A waypoint is assumed to be a point in the four-dimensional aircraft state space

$$W=[x, y, z, t] \tag{1}$$

where x, y, z , t - represent spatial coordinates of an aircraft and time.

Some of the waypoints, crucial to the mission of the flight, are to be designated as the target points.

The state of an aircraft at any moment of time, t_i , i=1,2,3, … is defined by vector

$$V(t_i)=[x(t_i), y(t_i), z(t_i), f(t_i), p(t_i), s(t_i)] \tag{2}$$

where

f – amount of fuel on board,

p – payload,

s – technical status, and

j – is the aircraft type index.

For the purpose of this project amount of fuel on board, payload, and technical status of an aircraft will be expressed in percent of maximum attainable.

State vector $V(t_i)$ is defined by a computation and/or by a status report. When the initial condition $V(t_{i-1})$ and the waypoint of interest $[x(t_i), y(t_i), z(t_i)]$ are known, the amount of fuel $f(t_i)$ is calculated by the designated software agent as follows,

$$f(t_i)= f(t_{i-1})- \delta f\cdot\tau \tag{3}$$

where

$\tau = t_i - t_{i-1}$,

$\delta f = \varphi_j[p(t_i)]$, j=1, 2, 3, … are different for different aircraft and depend on its specific configuration (Standard Configuration Load - SCL) and payload. These functions are defined by a special database. Note that the altitude and the increment of the spatial coordinates between t_{i-1} and t_i moments have little effect on the fuel burn rate for particular aircraft.

While technical characteristics of the aircraft, $\varphi_j[\dots]$, j=1, 2, 3, … known as burn rate functions may be classified, for the purpose of this project, the choice of these functions reflects only the expectations of the members of the project team who do not have any access to classified information.

It should be noted that quantities $f(t_i)$ and $p(t_i)$ could be known directly from the automatic reporting system and/or pilot's report, in this case the reported value will replace the calculated value. The payload $p(t_i)$ is expected to change upon reaching some target points or reported by the pilot, again, the reported value will replace the calculated value. The aircraft status, $s(t_i)$, reflecting the possible battlefield damage is expected to be reported by the pilot.

7.1. Acquiring relevant information

Relevant information will be organized in the three classes, one containing time-invariant data that has to be accessed only once per planning process, the second, containing time-varying data that has to be accessed at each step of the planning procedure, and the third one, that constitutes the reports that drive the planning procedure.

Time-invariant data is obtained from

Database-1 containing geographical information (digital map),

Database-2 containing performance characteristics of aircraft (fuel burn rates for particular aircraft and SCL),

Database-3 containing coordinates of the friendly airbases, and

Database-4 sizes of the air corridors and tunnels, and communication, alert, safety and collision zones around aircraft

Time-varying data is provided by

Database-5 containing the plan of the air operation,

Database-6 – weather information,

Database-7 – status and coordinates of targets, and

Database-8 – hazardous and restricted areas (special use air space)

Reported data is organized into

Database-9 that includes payload status (%), technical status, and fuel status (%), and actual aircraft position

Output data is defined by Database-10

7.2. Initial planning

The first step of the initial planning process begins from establishing a logical time schedule for the neutralization of particular targets. This is followed by assigning aircraft/weapons to particular targets, selection of departure airbases, and the bases where aircraft are to return after the completion of the mission. The resultant information is summarized as three or more target points

$$P_n[x(k), y(k), z(k), t(k)] \tag{4}$$

where

n=1,2,3, … represents particular aircraft,

k=1,2,3, ….correspond to the airbase of departure, designated target(s), and the airbase of return,

x(k), y(k), z(k), t(k) are spatial and temporal coordinates of the target points.

It should be emphasized that only t(k) values representing arrival times to the target locations, crucial for the air operation, are to be pre-specified. Temporal coordinates of the rest of the target points are to be calculated based on the average speed of the aircraft and the geometrical distance between the appropriate locations.

At the second step if the initial planning all intermediate way points are to be calculated by interpolation assuming that the target points are connected by straight lines in the four-dimensional space. The number of waypoints is defined according to some chosen time step T.

The third step of the initial planning is aimed at the detection and resolution of the conflicts thus resulting in addressing the following issues:

1. Traffic hazards
2. Current en route weather hazards
3. Rational airspace utilization
4. Aircraft-to-airspace separation
5. Aircraft-to-aircraft en route separation
6. Aircraft-to-aircraft separation in terminal airspace
7. Aircraft-to-terrain / obstacle separation
8. Current Surface Separation

Airspace design using space-based criteria (separation criteria) are developed based on the capability of aircraft to accurately fly and maintain pressure altitudes in higher altitude cruise and based on the capability of the aircraft and the relationship to separation criteria in lower altitude situations. Airspace design criteria for flight objects for a special use (hazardous/restricted) airspace activity that include the time duration and volume of airspace around the trajectory required to execute the mission. This addresses dynamic airspace restrictions with variable separation for security, military operations, remotely operated aircraft and reusable launch vehicles.

It should be emphasized that detection and resolution of the conflicts is to be done on the basis of weather condition, time of the air operation and the geographical region that dictate the sizes of the air corridors, air tunnels, and communication, alarm and danger zones surrounding aircraft (see airspace design criteria).

7.3. Current planning/execution

It could be summarized that the initial planning has three special features: it addresses primarily geometric considerations, it does not utilize the time-dependent state of the aircraft, and it does not rely on the "feedback information" representing the actual state of the aircraft. Consequently, it is performed only once prior the air operation. The current planning/execution stage constitutes an on-going effort reflecting continuously changing details of the air operation, such as neutralized targets, neutralized and newly detected hazardous zones, newly detected targets, deviations of the aircraft from their scheduled paths, changing technical status of the aircraft, etc. In addition, current planning is to be performed on a smaller time step, $\tau \ll T$.

7.4. State assessment task

The ever changing state of the particular aircraft i.e. its three spatial coordinates, amount of fuel on board, payload and technical status are taken into account by designated software agents at every step of the planning procedure,

$$t_i = i \cdot \tau,\ i = 1,2,3,\ldots \tag{5}$$

a) Calculated aircraft state data at time t_i

Spatial coordinates are obtained by the interpolation on the basis of the paths defined by the initial planning. Amount of fuel on board is calculated on the basis of the characteristics of the particular aircraft type and SCL and the payload $p(t_{i-1})$. The payload $p(t_i)$ is assumed to be equal to its previous value, $p(t_{i-1})$, unless waypoint $x(t_{i-1})$, $y(t_{i-1})$, $z(t_{i-1})$ is a target point representing an enemy target. The technical status of the aircraft, $s(t_i)$, is assumed to be equal to its previous value, $s(t_{i-1})$

b) Reported aircraft state data at time t_i

Reported spatial coordinates are obtained by the means of radar and/or GPS. The amount of fuel on board, payload, and the technical status (battlefield damage) of the aircraft are reported by the pilot. Note that for the planning purpose any information reported during the time period

$$[t_{i-1},\ t_i] \tag{6}$$

overwrites the appropriate calculated aircraft state data at time t_i

7.5. Deconfliction task

This task is aimed at the detection and resolution of the conflicts thus resulting in addressing the following issues:

1. Traffic hazards
2. Current en route weather hazards
3. Rational airspace utilization
4. Aircraft-to-airspace separation
5. Aircraft-to-aircraft en route separation
6. Aircraft-to-aircraft separation in terminal airspace
7. Aircraft-to-terrain / obstacle separation
8. Current Surface Separation
9. Special use (hazardous/restricted) airspace activity

It should be emphasized that detection and resolution of the conflicts is to be done on the basis of weather condition, time of the air operation and the geographical region that dictate the sizes of the air corridors, air tunnels, and communication, alarm and danger zones surrounding aircraft, i.e. parameters that constitute the airspace design criteria.

Unlike the initial planning, conflict resolution implies a negotiation process that takes into account (a) technical status of the involved aircraft, (b) amount of fuel on board the involved aircraft, (c) impact of the proposed maneuver on the amount of fuel, and (d) the impact of the proposed maneuver on the overall schedule of the air operation.

7.6. Methods of Deconfliction

The specific negotiation-based conflict resolution procedures have been developed and implemented in multi-agent environment originally suggested by

R. Schulz, D. Shaner, and Y. Zhao. Free-flight concept, *Proceedings of the AiAA Guidance, Navigation and Control Conference*, pages 999–903, New Orelans, LA, 1997,

C. Tomlin, G. Pappas, and S. Sastry. Conflict resolution for air traffic management: A case study in multi-agent hybrid systems, *IEEE Transactions on Automatic Control*, August 1997, and adopted and specially developed for the purpose of this project by M. Pechoucek at al., see

“Autonomous Agents in Air-Traffic Control”, Final Report to EOARD on project FA8655-04-1-3044-P00001, extension of the FA8655-04-1-3044 contract, Gerstner Laboratory – Agent Technology Group, Department of Cybernetics, Czech Technical University Prague, Czech Republic

AGENTFLY - FA8655-04-1-3044-P00001, Gerstner Laboratory – Agent Technology Group, Department of Cybernetics, Czech Technical University Prague, Czech Republic

The proposed deconfliction mechanism is distributed by its nature that allows for addressing the high volume of computations associated with the solution of this problem. The aircraft are modeled by agent containers hosting several agents, representing particular aircraft. An agent is a self-interested entity that is in charge of (i) preparing a detailed flight plan for the airplane respecting time-specific waypoints for the airplane's mission and (ii) executing the detailed flight plan by performing the simulated flight. For the purpose of implementing agent-based deconfliction procedure, each simulated aircraft is surrounded by a number of concentric spherical zones: communication, alert, safety and collision zones. *The communication zone* is the outermost one. It represents the voice communication range of the transponder and data transmitter onboard the aircraft. Using this data, the aircraft can send data packets to other aircraft that are positioned within the specified spherical zone defined by its radius. The *alert zone* defines the operation range of the radar onboard the aircraft. If another aircraft is located within the alert zone, the aircraft are periodically notified about its relative position and its flight code. The *safety zone* encapsulates the area around an aircraft that other aircraft are not allowed to enter in order to assure the safe operation of each aircraft. The size of this zone is not constant, but is determined by the aircraft type, its current tasks and the environment, allowing higher degree of freedom when the environment is adversarial. Safety zone radius can change dynamically during the flight. If two aircraft do enter each other's safety range, they can still continue flying but their flight path may be influenced by e.g. turbulence. This is not the case when two or more airplanes fly together in a close formation. The *collision zone* is the innermost zone. It defines the critical contact area. When the mutual distance between two aircraft is smaller than the sum of their collision zone radiuses, the physical collision happens.

The deconfliction has two formats, cooperative and non-cooperative.

Cooperative deconfliction is intended for the encounter of two or more friendly aircraft. It implies that the agents representing the involved aircraft avoid collisions *cooperatively* by negotiation. The negotiation starts as one aircraft enters the alert zone of another. It includes the on-going exchange of the state information and plane ID and consequent negotiation. It is important that the negotiation procedure takes into account all state components, including the position, amount of fuel on-board, and technical status of the aircraft. The nature of the negotiation mechanism is described in

J. C. Hill, F. R. Johnson, J. K. Archibald, R. L. Frost, and W. C. Stirling. “A cooperative multi-agent approach to free flight”, *AAMAS*, pages 1083–1090, 2005,

Non-cooperative deconfliction includes the detection and avoidance of such obstacles as terrain, structures, hazardous zones, local weather phenomena, and in addition, autonomous air vehicles and enemy aircraft. The procedure includes the collision detection, i.e. the algorithm that analyzes flight paths and tests the safety range violation, and the rule-based flight path modification, that may also include the analysis of the potential conflicts caused by this modification, see

J. C. Hill, F. R. Johnson, J. K. Archibald, R. L. Frost, and W. C. Stirling. “A cooperative multi-agent approach to free flight”, *AAMAS*, pages 1083–1090, 2005.

7.7. Data representation

Data representation will feature three displays:

The “big picture” display representing the entire battlefield situation, the conflict display featuring areas of potential conflicts, and the individual pilot’s display featuring its individual path and the areas of potential conflicts. The displayed information will include a fraction of the path of each aircraft within the waypoints of interest,

Data Structure/Format

Dependable operation of the computer-based air traffic control system requires access to several existing databases, including those containing sensitive and classified information. The project teams, including a Czech Multi-Agent System Technology group, do not have access to classified information and are not authorized to use sensitive information. Moreover, application of semi-autonomous software agents, especially those developed in foreign countries does not constitute an advisable database scanning technology. Existing unclassified “training” databases while representing the actual data structure contain effectively random numbers that are unsuitable for any reasonably realistic demonstration of the developed technology. Consequently, at the current stage of the system development all relevant data is placed in the following databases containing improvised, but realistic looking data expressed, when applicable, in relative units.

The data is organized in the following classes: time-invariant data, time-varying data, reported data, and the output data.

Time-invariant data

1. Database 1 contains geographical information (digital map). According to the project specification, the geographical region is to be specified via the system portal available on the Internet to authorized users. At the present stage of the project, for the purpose of presentation, only one geographical region, Mojave Desert, is available.

2. Database 2 contains fuel burn rate of aircraft

Table 1. Fuel Burn Rate Of The Aircraft

Aircraft index	Aircraft Type	Standard Configuration Load	Fuel burn rate (% of full tank per hour)	
			Full Load	Unloaded
1	F15E	4M82J3	20	12
1	F15E	8G27J2	31	14
1	F15E	2G27J3	18	12
2	F16C	4M84G2	19	14
2	F16C	6M84G3	20	16
2	F16C	2G27J3	16	14
3	B52H	55G31	8	7
3	B52H	31V31	7.5	7
3	B52H	6A88	7.8	7

3. <u>Database 3</u> contains coordinates of the friendly airbases

Table 2. Coordinates Of The Friendly Airbases

Base index-Name	X Degrees, minutes, seconds	Y Degrees, minutes, seconds
1-Name		
2-Name		
3-Name		
4-Name		

4. <u>Database 4</u> contains sizes of the air corridors and tunnels, and communication, alert, safety and collision zones around aircraft

Table 3. Communication, Alert, Safety and Collision Zones Of The Aircraft, Sizes Of The Air Corridors and Tunnels

Air space element	Size
Corridor	±100 ft
Tunnel	±500 ft
Communication zone	150 n miles
Alert zone	15 n miles
Safety zone	5 NM
Collision zone	1 NM

Time-varying data

1. Database 5 contains the plan of the air operation (NLT – not later than, NET – not earlier than)

Table 4. Plan Of The Air Operation

Aircraft index	Aircraft ID	Aircraft type	Departing base index	Returning base index	Targets					
					Target 1			Target 2		
					index	Time NLT	Time NET	index	Time NLT	Time NET
1	M123	2	3	3						
2	C511	3	6	2						
3	V1341	7	1	3						
…	E1205	…	…	…						

2. Database 6 contains weather information: not used

Table 5. Weather Information

Reported time frame		Weather Factor	Intensity on the scale 0 to 10	Time			Weather classifier
				Day	Night	Dusk	
1407	1600	Rain	7	1	0	0	8
		Snow	0				
		Thunderstorm	2				
		Fog	5				
		Visibility	3				
1524	1900	Rain	0	0	0	1	12
		Snow	0				
		Thunderstorm	1				
		Fog	6				
		Visibility	2				

3. Database 7 contains status and coordinates of targets

Table 6. Status And Coordinates Of Targets

Target Index	X-coordinate (Longitude) Degrees, minutes, seconds, deciseconds	Y-coordinate (Lattitude) Degrees, minutes, seconds, deciseconds	Target description	Status
1			Radar station antenna	active
2			Air base, center of runway	active
3				
4				
5				
6				
…				

4. Database 8 defines hazardous areas

Table 7. Hazardous Areas

#	Cylinder			Layer								High miles	Low miles	Description	Status
	Center		Radius miles	X 1	Y 1	X 2	Y 2	X 3	Y 3	X 4	Y 4				
	X	Y													
1	xxxx	yyyy	RRRR									hhhh	hhhh		A
2				xxx	yyy	xxx	yyy	xxx	yyy	xxx	yyy	hhhh	hhhh		A
3				xxx	yyy	xxx	yyy	xxx	yyy	xxx	yyy	hhhh	hhhh		IA
4				xxx	yyy	xxx	yyy	xxx	yyy	xxx	yyy	hhhh	hhhh		A
5	xxxx	yyyy	RRRR									hhhh	hhhh		A
6	xxxx	yyyy	RRRR									hhhh	hhhh		IA
7	xxxx	yyyy	RRRR									hhhh	hhhh		A
..															

Reported data

1. Database-9 includes payload status (%), technical status (%), and fuel status (%)

Table 8. Payload, Technical And Fuel Status

Time	Aircraft ID	Payload	Fuel	Tech. Status			Position			Velocity
				Performance degradation, %	Weapon delivery capability Y/N	Physical status %	X	Y	Z	

Output data

The output database generated by the system will include the following information. Dazta format must be acceptable for the J-view display

Table 9. The Output Database Generated By The System

	Aircraft ID												
	M123						C511						V1341
time	C511	Y	Z	P	F	S	X	Y	Z	P	F	S	…
1205													
1210													
1215													
1220													
1225													
1230													
….													

8. IMPLEMENTATION: AGENTFLY BY GERSTNER LABORATORY

AGENTFLY is a software prototype of a multi-agent simulator of unmanned aerial vehicles air traffic control supporting the free fight concept. All aerial assets in AGENTFLY are modeled as asset containers hosting multiple intelligent software agents. Each container is responsible for its own flight operation. The operation of each vehicle is specified by an unlimited number of time-specific, geographical way-points. The operation is tentatively planned before take-off without consideration of possible collisions with other flying objects. During the flight performance, the software agents hosted by the asset containers detect possible collisions and engage in peer-to-peer negotiation aimed at sophisticated re-planning in order to avoid the collisions. The implemented simulator demonstrate readiness of the multi-agent technology for distributed, flexible, and collision-free coordination among heterogeneous, autonomous aerial assets (manned as well as unmanned) with a potential to (i) fly a higher number of aircrafts, (ii) decrease requirements for human operators and (iii) allow a flexible combination of cooperative and non-cooperative collision avoidance.

AGENTFLY is build on top of the *A*-globe multi-agent platform. *A*-globe provides flexible middleware supporting seamless interaction among heterogeneous software, hardware and human actors. *A*-globe outperforms available multi-agent integration toolkits by its ability to model rich environments in which agents interact, by its support of full code migration and by its support for scalable experiments. Current AGENTFLY implementation provides a distributed model of flight simulation and control, time-constrained way-point flight planning algorithm avoiding specified no-flight zones and terrain obstacles, flexible collision avoidance architecture {cooperative and non-cooperative, connectors to external data sources (Landsat images, airports monitors, no-flight zones, cities), 2D/3D visualization including a web-client access component, and a multi access operator - a component facilitating real-time control of selected assets.

The present work mainly addresses the problem of distributed collision avoidance among autonomous aerial assets using multi-agent technology {each UAA is represented by an agent container hosting different functional agents. Each UAA is controlled by a single, dedicated agent. The presented collision avoidance architecture provides capability to integrate several different collision avoidance algorithms that plan the runtime trajectory of each individual UAA.

Such architecture supports operation of the group of cooperative UAA within the environment hosting other non-cooperative flying objects (e.g., civilian air traffic or manned aircrafts in the same area). Cooperative collision avoidance, the deconfliction process between two or more interacting and cooperating aerial assets, is based on using different collision metrics and negotiation protocols. Recently, the centralized solution has been replaced by various distributed approaches facilitating deployment of e.g., principled negotiation, Monotonic Concession Protocol (MCP) for collision avoidance in between of two assets or extensions towards groups of multiple UAAs. Such approach can be slightly altered to optimize social welfare instead of individual goals in the group of UAAs. There are also various approaches based on the game theory available in the research community.

Optimization of non-cooperative collision avoidance algorithms (deconfliction process of an individual aircraft facing a non-cooperative, possibly hostile object) allows optimal solving of the collision with a non-cooperative flying object (obstacle). These algorithms perform well when coping with a single alien flying object, but they cannot be extended to a situation with several flying objects, located nearby. Moreover they cannot be used simultaneously with other cooperative algorithms applied for the cooperative collisions at the same place. The research work was motivated by designing such a non-cooperative collision avoidance method that does not suffer from these weaknesses.

A comprehensive description of the AGENTFLY and its operation could be found in the following publication:

> David Sislak, Michal Pechoucek, Premysl Volf, Dusan Pavlicek, Jiri Samek, Vladimir Marik and Paul Losiewicz, "AGENTFLY: Towards Multi-Agent Technology in Free Flight Air Traffic Control", Whitestein Series in Software Agent Technologies and Autonomic Computing, 77{100 2007 BirkhÄauser Verlag Basel/Switzerland

9. SYSTEM TESTING/VALIDATION

Testing/validation of the developed technology was performed by

1. Establishment of the realistic characteristics of the aircraft (speeds, payload, available fuel, etc.) and design parameters of the airspace (separation criteria)
2. Establishment of the realistic practices of interaction between air traffic controller and pilots, and between pilots (such as usage of RF communication)
3. Further enhancement of interactive graphics and visualization
4. Development of a realistic scenario for the demonstration of the developed system, emphasizing its advantages over the existing practices.

Scenario

The scenario addresses the requirement to preclude fratricide between members of a force package composed of heterogeneous manned aircraft missions and surveillance unmanned aerial systems (UAS) in a target complex composed of multiple Desired Mean Point of impacts (DMPI) as well as the addressing the package assembly at the rendezvous point prior to ingress into enemy territory.

The force package will be composed of B52H, F15E and F16C strike missions with supporting EA6B Electronic Warfare (EW) platforms F15C escort and F16CJ Suppression of Enemy Air Defense (SEAD) assets.

Each of the missions within the package come from different departure bases additionally the F16CJ will require air refueling prior to the rendezvous point If we consider the package rendezvous point to be the entry of a corridor through the air defense threat along the battle edge and will be used by many packages and independent missions then the system must consider the actions of demonstration package as well as others using the corridor entry point.

The departure bases are labeled A thru G for the demo package as shown on the pictorial The B52H mission (MSN) 1234 will depart from base A as a single ship mission assigned DMPI‘ INT 001, INT002, OCA 001 and OCA 002. A second single ship B52H mission also departs from base A, MSN 4321, with DMPI OCA 010, OCA 011 and OCA 012 and INT 002 as a secondary target. There are two F15E missions each composed of 4 aircraft and depart from different bases both missions have two targets. MSN 5678 has DMPI INT020 and INT021 and departs from A while MSN 6788 has DMPI OCA015 and OCA016 and departs from base B. The F16C strike mission is composed of 4 mission aircraft with two targets DMPI INT 031 and INT 032 and depart from Base D and refuel at Texaco high prior to the rendezvous They receive fuel from MSN T123 a KC135R aircraft that departs and recovers at base E. The SEAD mission is composed of two F16CJ aircraft loaded with Home on Active Radar Missiles (HARM) that depart from Base G and establish orbits in the package target area to provide suppression coverage for the fighter mission in the package. They also provide SEAD for package ingress and egress. The B52H missions provide self-protection and also assist in SEAD coverage of the target complex for the other package members. The F15C depart Base C and provide escort coverage for the package and once in the target complex area establish Combat Air Patrol (CAP) orbits to protect the package once it breaks up for target prosecution and re established at the rejoin point for egress.

NOTE *Currently the Air Operations Center (AOC) assigns the Rendezvous point its time the air refueling contact time and the time on targets (usually a not earlier /not later time) It is the package commander assigned by the AOC that must coordinate the specific altitude/ and mission associations to preclude mission fratricide . The congestion at the corridor ingress point between different packages is de-conflicted by the airborne C2 platform usually the AWACS but if the packages do not have knowledge between each other this de-confliction is only done through time of entry to the corridor and holding orbits may be required to get though the corridor The problem get even more complex on the egress corridor as the entry to it may not be within radar coverage of the AWACS and enemy involvement with the missions/packages make specific timing near impossible to procedurally define . Therefore there are more egress corridors available and procedurally blocks of time made available for missions/packages to egress but many missions do not make the assignment.*

For the demo we could have our package get to the entry /rendezvous point at the same time as another package [our package has a problem with a late arrival of the tanker at Texaco (5 minutes late) which slipped the time of arrival by 5 minutes while winds aloft make the other package 5 minutes early.

Package Two is composed of just four missions a single B52 mission, a mission of two F15E's an EA6B SEAD mission and Escort F15C in support. The targets are not important but what is important is they use the same ingress point and are scheduled at the ingress at only 10 minutes apart.

Once at the Target Complex (package break out point) the attack mission to go there separate ways to attack their assigned DMPI based on their individual mission plans with the package commander attempting to provide de-confliction within the target area. The exact sequence of targets, unless specified by a discrete TOT, to be attacked is determined by each mission.

NOTE S*ince the missions are planned at different bases the specifics of the route between each DMPI are not known by each package participant as there are being planned and route between DMPI is not part of the ATO nor de-conflicted effectively since missions vary their path between DMPIs to align with attack target run in headings and maneuver to avoid threat lock- on.*

UAS doing Intelligence, Surveillance, and Reconnaincence (ISR) collection are also within the Target Area along with the package however these assets are employed either on preplanned mission profiles which can not be easily altered within the mission without canceling the mission or are under the direction of a mother ship which may not have continuous connectivity with the UAS. Therefore the deconfliction with these assets becomes the premise of the Package. The first UAS asset (predator) is not continuously guided and is to fly at a medium altitude say 15,000 ft and collect photographic battle damage data to allow a Battle Damage Assessment to be done. It is timed to collect both pre attack and post attack sensor data on target OCA010 an OCA015. These tasking places these non-cooperating assets within the target area along with the attack package. A second UAS mission is composed of an active jammer payload on a Global Hawk used to cover specific frequency ranges not within the range of the EA6B and provide SEAD for this package as well as other packages at different times and places behind enemy lines. The distance places limited control over the flight paths of these assets from an EC130J in orbit on the friendly side of the battle line so maneuvering by the UAS is very limited to avoid fratricide with the package and their altitude coincides with those used by the EA6B and F15C CAP orbits.

At the completion of the attack sequence of each mission the package reforms at a rejoin point and can proceeds to the egress corridor.

NOTE *In order to get the package into a cornice group certain package members will be required to delay or speed up to make the group formation. This requires radio communication between package members some thing that aircrew would like to keep to a minimum as it gives away mission information that the enemy can use to attack the package.*

Once the package exits the egress corridor the package breaks up and procees back to either their post strike refueling or recovery base. .In or demo scenario the F15E MSN5678 must refuel at Texaco as well as the EA6B. Plus do to battle damage inflicted by small rounds the F16CJ will need to get fuel at Texaco but does not have a pre planned post refueling and the system must de conflict the F16CJ with the post refueling other missions at Texaco.

NOTE *this task is normally performed by the AWACS but has no tools to work the sequence to assure the Air Refueling Contact Time (ARCT) and receive fuel time do not overlap with preplanned refueling. Also how to have selected receivers delay/speedup their missions to make space for the battle damaged fuel needs In the demo we could delay the EA6Bto get a later ARCT and speed up the F15E MSN 5678 from package break up to gain an earlier ARCT thereby making space for the F16CJ mission*

The developed scenario has been successfully implemented in the developed software system clearly demonstrating, the feasibility, vitality, and efficiency of the developed multi-agent system. Multiple CDs featuring the presentation has been burned and distributed to appropriate agencies.

10. POSSIBLE INTERFACE WITH THE EXISTING SOFTWARE

JASMAD dynamically manages the airspace volume by usage and allocates them for use buy missions but does not manager the routes aircraft fly within the airspace so unless positive control (AWACS) is available it's a “see and be seen” route deconfliction. This is where our project comes into play by deconfliction mission routes within the allocated airspace fratricide is eliminated and dependency of positive control is not necessary. There are many scenarios that would place an AWACS in harms way for them to provide positive control i.e. a SAM threat especially mobile. Also as the UAV become smaller they become more difficult or near impossible for the AWACS to deconflict. But we can! Since the airborne objects work out the deconfliction, positive control is not required and using UAV mission positional data at the "mother" ship, UAVs can negotiate mission route deconfliction especially when one has a problem and operates as rouge (treat as a non-cooperator). However we would benefit from JASMAD's air volume management and assure that deconfliction routes do not violate airspace assignments especially air refueling airspaces. Many airlines and some general aviation aircraft have avoidance warning systems TAWS but they only warn and do not provide a solution to the potential conflict. By integrating the two projects we would truly have the air over the combat environment managed. With only JASMAD you manage the volume not the entire environment. The introduction of waves of UAV's and the associated fratricide issues will not be solved by managing the air space but managing the routes within the air environment. We need the dynamic airspace data JASMAD provides such as ROZ and Missile Engagement Zone (MEZ) etc. so that we can assure the solution does not violate these zones.

Desired scenarios

If a UAV drops guidance our system would consider it a non-cooperator and manipulate the routes of those objects that are cooperating to preclude fratricide. Since the rally point is known we could assure vacancy of that point at a safe time window by treating the point as a ROZ for the managed objects. Most of the problem with UAV that are not responding can be handled as non cooperators and the managed object routes will deconfliction from the non cooperator. In summary:

1) UAV Goes Lost Link – Our system treats UAV as a non-cooperating object and modifies the appropriate aircraft' paths to avoid it.

2) Priority Aircraft Needs Transition Through Airspace – resolved by the very nature of the negotiation process that is intended to address the priorities issue. Controlled UAVs are expected to have low priority in the negotiation process and will be given new corridors.

3) UAV Engine Failure – the UAV will be treated as a non-cooperating object.

4) Tracking a Target – there is a provision for mobile waypoints

5) Pop-up Restricted Area – there is a provision for dynamic no-fly zones

11. RELEVANCE TO FAA PLANS

Air Route De-confliction within the National Airspace System (ARDNS)

Purpose: To integrate an automated air route de-confliction capability as a segment of the Federal Aviation Administration (FAA)'s Next Generation Air Transportation System (NexGen)

Problem: As the air passenger traffic has increased not only has the airport ground and runway congestion become a problem for the National Air System (NAS,) but it also introduces a route de-confliction issue to the air route structure utilization along the FAA designated routes. This increased utilization of FAA routes has been further compounded by the airline industry's move to smaller airframes for continental United States traffic as well as a larger utilization of regional jet operations that carry a smaller passenger load, but introduce many more aircraft along defined routes into the NAS.

The increased utilization of Global Positioning System (GPS) Direct traffic by the Business and General Aviation (GA) has introduced additional potential for route conflicts to this saturated FAA route environment.

Background: The FAA's NexGen vision introduced programs into the NAS. Of specific interest to route saturation and conflict identification is the Automatic Dependent Surveillance – Broadcast (ADS-B) program. Additionally, the utilization of Traffic Alert & Collision Avoidance Systems (TASC) by many airline and business aviation users has increased the safety of the NAS. However, other than establishing conflict visualization and alerting environment, it does not provide de-confliction guidance or resolution methodologies.

The ADS-B periodically transmits operation information without a pilot/operator input requirement. The broadcast contains position and velocity vector information that is derived from the aircraft GPS or a Flight Management System (FMS). The Traffic Information Service - Broadcast (TIS-B) provides the ADS-B equipped aircraft with position reports from secondary surveillance radar for non ADS-B equipped aircraft generated by their Mode S transponder broadcasts. .This provides ADS-B equipped airframes with surveillance and identification of en-route, terminal and surface conflict detection, but without any conflict resolution.

ARDNS was developed, tested and demonstrated by XXXX under contract administered by the Air Force Research Laboratory (AFRL) - Rome as an advanced research project. The program utilized cooperating software agents to solve a Many on Many air route de-confliction problem. Upon request, a Digital Video Disk (DVD) is available that demonstrates the capability of ARDNS and the software approach used to solving the route confliction issue. When the standard de-confliction FAA procedure was compared to ARDNS, ARDNS was found to be far more fuel conservative and required much less aircraft maneuvering to solve the conflict. What the comparison also showed was that in intense aircraft environments the FAA procedure many time may solve the immediate conflict, but it introduced additional conflicts and, in fact, produced a snow ball effect in which de-confliction became unmanageable when the density of airframes was introduced The testing was performed to determine the extent that not only cooperating air vehicles such as those with TIS-B and TACS, but with non-cooperating assets such as stealth and Remotely Piloted Vehicles RPV. In order to evaluate the capability within a combat environment which would exceed the issue faced by the NAS, a test scenario was develop with multiple aircraft package missions coming from multiple departure bases converging on a target area with Time on Target (TOT)'s that overlapped. The ARDNS was capable of de-conflicting these mission packages as well as the RPVs within the target area. The DVD available also has this scenario run as part of the demonstration. This combat environment had both cooperating agents and non-cooperating agents and was de-conflicted in real time.

Currently over 25,000 airframes are equipped with a TACS II capability and by 2020 it assumed that all aircraft would have some form of ADS-B capability including Business and GA.

ADS-B provides the broadcast informational environment upon which ARDNS could be implemented. In fact, it might be possible once ARDNS is part of the NexGen to reduce the separation requirement even below the three mile separation provided by En Route Automated Modernization (ERDM) capability.

Possible Proposal: It is proposed to integrate into the NexGen NAS a system that not only alerts aircraft to route conflict, but provide a real time avoidance route direction. The de-conflicted route defined by ARDNS deals with a total relationship with all other aircraft within a specified airspace environment and provides selectable separations currently set to five miles. ARDNS also attempts to minimize globally the route perturbations necessary to deconflict the converging airframes, such as minimizing the distance an airframe is diverted from its original planned route, to minimize climbs and descents necessary to preclude a conflict and to reduce the necessity to hold along the route of flight. The system can deal with non-participating aircraft whether RPV, Stealth, or non ADS-B capable and incorporate them into the decision environment.

The proposed effort will have three segments in which the ARDNS will be expanded and interoperated within the NAS. The first segment will allow the ARDNS to interface with the ADS-B broadcast protocol and Mode S transponder code in order to develop the necessary data for ARDNS to determine de-conflicted routes. The routes will be available for use by FAA Air Route Traffic Control Centers (ARTCC). This phase will demonstrate ARDNS de-conflicted routes incorporated into the ARTCC upgraded air traffic display consul. The design will allow the ARDNS defined route modifications to be displayed as well as providing the ARTCC controller a source for traffic directions that can be transmitted to affected aircraft via voice communication.

The second segment will address the data needs and communications changes necessary for TIS-B to incorporate ARDNS directions to ADS-B equipped aircraft. Additionally, this segment will develop a demonstration of integration of this TIS-B enhanced data flow on a Capstan Multi-function Display (MFD) such as the GDL-90 UAT or GNS 500 manufactured by Garmin.

The third segment will utilize the “breadboard” MFD capability developed in segment two as the bases for validation demonstrations of ARDNS working in a realistic ADS-B environment. Multiple test scenarios will be developed that contain route conflicts to stress ARDNS TIS-B instantiation. The test will require a minimum of three environments with aircrew member as test subjects to validate the actions identified by ARDNS. The test subjects will validate that the actions proposed are, in fact, realistic and flyable by both airline and GA aircraft.   As part of these demonstrations, non-ADS-B equipped airframes will be treated in ARDNS as non-cooperating assets.

Given a successful demonstration of ARDNS capabilities, further expansion of the capability could be further interfaced into many vendor Flight Management Systems (FMS) and ADS-B capability. The ARDNS capability could be tied to auto pilots through the FMS and automatically establish route de-confliction actions once the FAA has validated ARDNS.

Of the three segments, segment one will require the major effort and would require 14 months to complete. While segment Two will only require nine months to complete, there is almost equal cost as interfacing and incorporating capability in a secondary vendor’s product will require an agreement with that vendor and may require them to do some additional interface work on the MFD. Segment Three will require six months of effort to develop these scenarios and have them validated by both the test subjects and the FAA.

12. REFERENCES

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Glossary

ACA	Airspace Control Authority
ACP	Airspace Control Plan
AF	Air Force
AFRL	Air Force Research Laboratory
AGENTFLY	Multi-agent software implementing the developed system
AOC	Air Operations Center
ARCT	Air Refueling Contact Time
ARTCC	Air Route Traffic Control Centers
ASA	Airspace Control Authority
DMPI	Desired Mean Point of Impacts
EW	Electronic Warfare
FAA	Federal Aviation Administration
FMS	Flight Management System
GPS	Global Positioning System
GUI	Graphical User Interface
ISR	Intelligence, Surveillance, and Reconnaincence
JASMAD	Joint Aerospace Management software
MCP	Monotonic Concession Protocol
MFD	Capstan Multi-function Display

NAS	National Airspace System
NET	Not Earlier Than
NLT	Not Later Than
OSD	Office of the Secretary of Defense
SEAD	Suppression of Enemy Air Defense
STL	Standard Configuration Loads
UAS	Unmanned Aerial Systems